Expansion of a Direct Simulation-Based Study of Radiance in a Dynamic Ocean

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LONG-TERM GOALS

The ultimate goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. The simulation-based model will include and integrate all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transport.

OBJECTIVES

To develop physics-based modeling and computational prediction and inverse capability for the time-dependent underwater radiative transport incorporating the dynamical processes on the ocean surface and the upper ocean surface boundary layer (SBL):

- Develop direct simulation of upper ocean hydrodynamic processes and forward prediction of radiative transfer
- Obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment
- Obtain direct quantitative comparisons and cross validations and calibrations of the model predictions and the field measurements of surface wave features and underwater radiance properties
- Provide a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data

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APPROACH

A simulation approach, based on direct physics-based simulations and modeling, is developed and applied to solve the problem of ocean-atmosphere radiance transport (RT) in a dynamical ocean SBL environment that includes nonlinear capillary-gravity waves (CGW), free-surface turbulence (FST) roughness, wave breaking, and bubble generation and transport. The radiative transport process includes multiple scattering in the atmosphere above, ray tracing at the water surface, and multiple scattering in the water underneath. The complex dynamical processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transport using direct Monte Carlo simulations including volume scattering and attenuation.

WORK COMPLETED

- **Direct quantitative comparisons between RaDyO field measurements and model prediction.** We performed quantitative comparisons incorporating all the key RaDyO wave, IOPs and underwater radiance measurements with combined wavefield (reconstruction and prediction) and RT (full unpolarized and polarized light field) modeling.

- **Data assimilation and inverse modeling.** We developed an approach for solving the inverse problem, based on the forward modeling of RT and computational fluid dynamics together with a reverse modeling using an adjoint model. In this approach both the wave dynamics and the RT simulation are built into a variational data assimilation scheme. The RaDyO measurements were used to verify the effectiveness of the approach.

RESULTS

We developed a 3D Monte Carlo (MC) RT simulation capability for unpolarized and polarized light for the atmosphere-ocean system. The model is systematically validated by direct comparisons with existing theories and numerical model predictions and with field data including RaDyo measurements. The developed 3D MC RT model is applied to investigate the characteristics of polarization distribution and underwater irradiance in various ocean surface environments.

(1) ***Effects of ocean surface waves on underwater polarization patterns:*** With MC simulation capability, effects of the ocean surface roughness on the underwater light polarized light fields were intensively examined. Figure 1a shows the dependence of the ratio of maximum mean value of degree of polarization to the sky degree of polarization $\langle P\rangle_{max}/P_{sky}$ on the mean square slope (MSS) of the ocean surface waves. Four different depths are considered and they are z=-0.3m, -2.2m, -4.9m, and -7.5m. The solar incidence is $\theta_{sun}=65°$ and $\varphi_{sun}=0°$; the light wavelength $\lambda=532$ nm; IOPs were obtained from the Santa Barbara Channel (SBC) experiment which are total beam attenuation coefficient $c=0.610$ m^{-1} and total single scattering albedo $\omega=0.873$; Petzold phase function was used. It can be seen that increasing surface roughness leads to smaller degree of polarization, and the relation between the maximum underwater degree of polarization and MSS is approximately linear. The dependence of maximum degree of polarization becomes weaker at deeper locations, indicating that the effect of ocean surface waves on polarization diminishes with detector depth.

Consideration of nonlinearity of surface waves is of critical importance in the study of underwater irradiance as it affects the profile of ocean-atmosphere interface. Figure 1b compares the effect of linear and nonlinear waves with same MSS and different MSS respectively on polarization in variance of the mean value of degree polarization $\langle P \rangle$ at the local maximum inside the Snell's window, at the position of $\theta=40°$ and $\varphi=110°$. $\langle P \rangle_{max}/P_{sky}$ induced by the linear waves with MSS=0.03 is a little larger than that of nonlinear waves. The variance of $P/\langle P \rangle$ at the local maximum point with nonlinear waves is larger than the variances of linear waves with the same and smaller MSS. Therefore, it can be expected that in the case of rougher sea surfaces where nonlinearity becomes more dominant, the variance of the in-water polarization is larger than the calculation based on a linear wave assumption.

(2) ***Variability of underwater irradiance induced by ocean surface wave:*** To understand the variability and fluctuation of the in-water light fields, we developed a statistical GP model that analytically quantifies the PDF of the downwelling irradiance under random ocean waves. The model assumes that ocean surface as independent and identically distributed flat facets. The theoretical model captures the characteristics of the PDF from skewed to near-Gaussian shape as the depth increases from shallow to deep water. It obtains a closed-form asymptotic for the probability that diminishes at a rate between exponential and Gaussian with increasing extreme values. Figure 2a shows the comparison of the PDF of normalized the downwelling irradiance $E_d/\langle E_d \rangle$ at the depth z=-2.85m with experimental data and predictions by MC simulation. It shows that a very good agreement with the three methodologies has been reached. Figure 2b demonstrates one application of GP model in understanding the how wind-driven ocean surface wave spectrum influences the PDF of underwater irradiance. It can been seen that increasing wind speed results in the monotonic decrease of the normalized irradiance standard deviation σ_χ and as increasing depth σ_χ rapidly approaches the deep water limit as the downwelling irradiance is dominated by volume scattering effect.

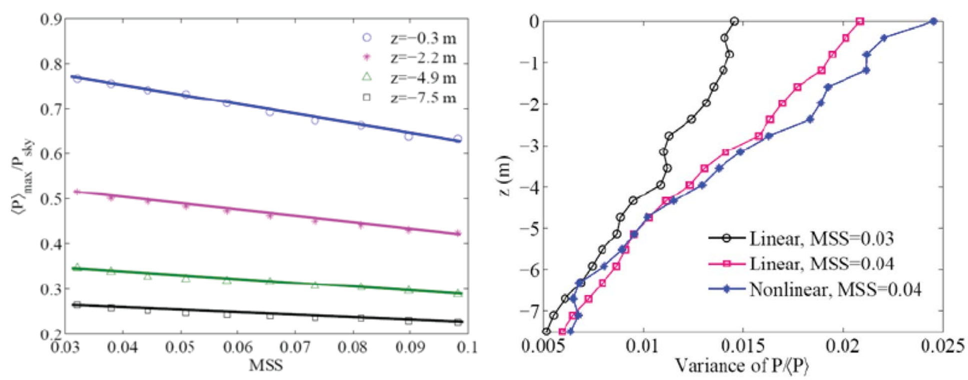
(3) ***Effects of ocean turbulence flow on underwater radiance/irradiance distributions:*** We consider the radiative transfer process within the inhomogeneous ocean turbulent flow. To solve the non-homogeneous radiative transfer equation with the variable refractive index, we developed the hybrid Monte Carlo method and ray-tracying technique to account for the light beam bending. Figure 3a shows the downwelling irradiance pattern at the depth of z=-80m caused by the progressive ocean surface waves and the turbulent flow beneath the surface. It can be seen that basic pattern of the downwelling irradiance is determined by focusing of light at the ocean surface and the pattern is blurred by the turbulent flow. Figure 3b shows the normalized standard deviations of the downwelling irradiance for the case of surface waves propagating in the same direction of the shear flow is considered for different turbulence kinetic energy (TKE) dissipation rate $\langle \chi \rangle$. We can see that higher TKE rate increases standard deviations of the downwelling irradiance slightly.

IMPACT/APPLICATIONS

The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of structures/objects on or above ocean surface based on sensed underwater irradiance data.

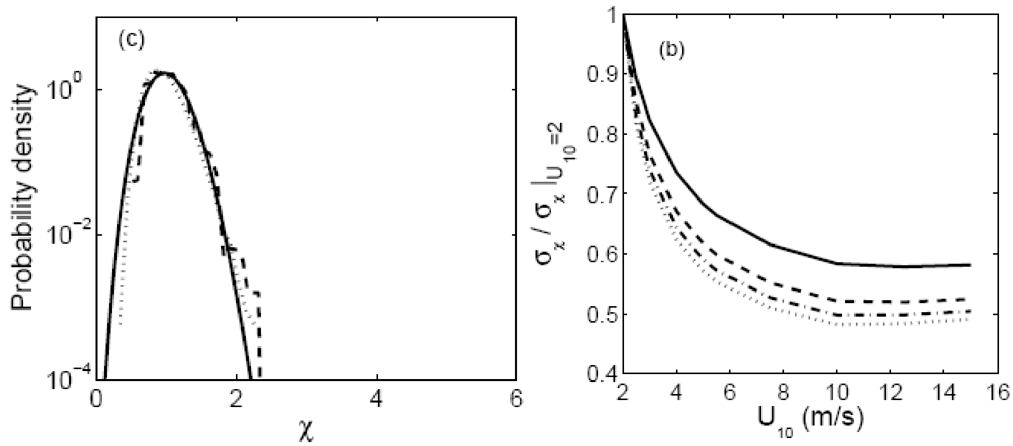
PUBLICATIONS

1. Sheng, M., Xu, Z. and Yue, D. K. P. 2011 A model for the probability density function of downwelling irradiance under ocean waves, Opt. Express, Vol. **19** (18), 17528-17538 [published, refereed]
2. Xu, Z., Yue, D. K. P., Shen, L. and Voss, K. 2011 Patterns and statistics of in-water polarization under conditions of linear and nonlinear ocean surface waves, J. Geophys. Res. [in press, refereed]
3. Xu, Z., Guo, X., Shen, L. and Yue, D. K. P. 2011 Radiative transfer in ocean turbulence and its effect on underwater light field, J. Geophys. Res., [Submitted]



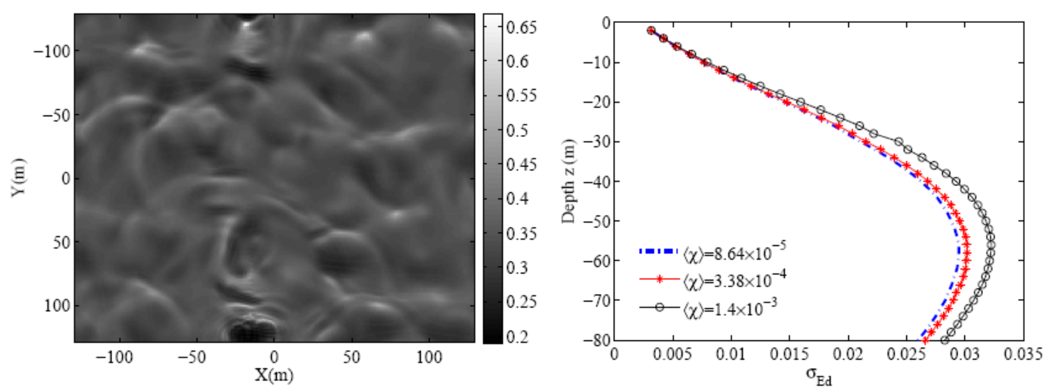
(a) (b)

Figure 1. (a) Dependence of ratio of maximum mean value of degree polarization to sky degree of polarization <P>$_{max}$/P$_{sky}$ within the Snell's window on the MSS of the ocean surface at different depths. (b)Effects of the nonlinearity of ocean waves: the variance of the normalized degree of polarization at different depths under linear and nonlinear waves with same MSS and different MSS.



(a) (b)

Figure 2. (a) Comparison of the GP theoretical model (—) for the PDF of the normalized downwelling irradiance χ=E/<E> with Monte Carlo (MC) simulation (•••) and experimental data (– – –) at depth of 2.85m. (b) Wind speed effect on standard deviation of normalized downelling irradiance σ_χ for different depths: Dcw_0= 0.524(—); 1.04 ((– – –); 1.74((–• –•) and DCw_0 →∞(•••).



(a) (b)

Figure 3. (a) Instantaneous downwelling irradiance E_d at z=-50 m within a turbulent flow under ocean surface waves of peak frequency steepness k_pa_p=0.1. (a) Normalized standard deviations σ_{Ed} of downwelling irradiance as the function of depth under progressive waves of propagating in the same direction as the shear flow for cases with different temperature dissipation rates <χ>.